Real world-based immersive Virtual Reality for research, teaching and communication in volcanology

Tibaldi A.[1], Bonali F.L.[1], Vitello F.[2], Delage E.[3], Nomikou P.[4], Antoniou V.[4], Becciani U.[2], Van Wyk de Vries B.[3], Krokos M.[5], Whitworth M.[6]

[1] Department of Earth and Environmental Sciences, University of Milan Bicocca, Italy
[2] National Institute of Astrophysics, Catania, Italy
[3] Observatoire du Physique du Globe de Clermont, University Clermont Auvergne, Clermont- Ferrand, France
[4] Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece
[5] School of Creative Technologies, University of Portsmouth, UK
[6] School of the Environment, Geography and Geosciences, University of Portsmouth, UK

Abstract

Direct outcrop observation and field data collection are key techniques in research, teaching and outreach activities in volcanic areas. However, very often outcrops are of difficult or impossible access, such as in areas with active volcanoes or steep cliffs. Classical remote-sensing surveys by satellites or airplanes are expensive, rarely reach sufficient resolution to allow high quality 3D visualisation of volcanic features, and do not facilitate mapping of vertical cliffs. We describe a novel approach that uses immersive Virtual Reality (VR) based on real world 3D Digital Outcrop Models (DOMs) from images surveyed by "unoccupied aerial system" (UAS). 3D DOMs are built up using the Structure-from-Motion (SfM) photogrammetry technique, and a VR scene is created using game engine technologies. Immersive real-time exploration of the environment is possible through a head-mounted display, e.g. Oculus Rift. Tools embedded in the VR environment allow the user to map polygons, lines and point features. Tools also allow to measure orientation, dip, inclination, azimuth, area, thickness and even take virtual photographs. Using three examples of volcanic areas with different geological features, we demonstrate the potential of our approach to allow users to be able to virtually map and measure remotely, and to collect data for research and teaching. Our approach is of paramount importance also for outreach, as it allows non-specialist audiences (e.g. common citizens) to experience and appreciate highly complex volcanic features through customised, hands-on immersive VR tools.

Key words: Volcanology, Teaching & Scientific Communication, Immersive Virtual Reality, Head-Mounted Displays

Introduction

Research activity, teaching and learning in volcanological sciences need the collection and observation of data in the field, which typically constitute the backbone of any applied study in petrography, geochemistry, geohazard, and many other areas. Outcrops can often be difficult to access for logistical reasons, or even impossible to inspect, e.g. in the case of steep or vertical cliffs. Data collection can also be dangerous, as in active volcanic areas with explosions, gas, hot fumes, etc., or other areas prone to geological hazards. Also, teaching and learning is classically based on 2D images, although geological objects are 3D; to overcome this problem, university geoscience courses typically include extensive fieldwork programmes, but these involve expensive and time-consuming trips.

In the case of extra-university communication addressing audiences within the society at large, including administrators, politicians, media and individual citizens, immersive Virtual Reality (VR) can allow different target groups to experience volcanic features in inclusive and novel (or otherwise impossible) ways. The term immersive VR refers to the perception of being physically present in a non-physical world. The perception is obtained by surrounding the user with images, sound or other stimuli, providing the feeling of being immersed in the environment. In Earth Sciences, this is essentially achieved by surrounding images (Granshaw and Duggan-Haas, 2012; Trexler et al., 2018; Zhao et al., 2019). As immersive VR can be fun, and different, it also engages people and allows them to express their thoughts and feeling about natural sites. This results in outreach and embracing communication, a two-way process that can help scientists understand the needs and opinions of society. Moreover, game engines have reached a high level of technological maturity offering rich toolsets of mechanisms for implementing 2D/3D visualisation and exploration workflows in immersive VR environments realised on dedicated game consoles, personal computers or mobile platforms (Andrade, 2015; Lawson, 2016; Christopoulou and Xinogalos, 2017).

Remote or dangerous volcanic areas have been classically studied by aerial or satellite remotely-sensed images, which have several limitations: 1) high-resolution data are very expensive to cover large-scale geological objects and the resolution can be poor for some targets, 2) it can be challenging to plan a specific survey by an airplane, due to high costs or remoteness of the site, 3) it is impossible to map steep to vertical slopes by images acquired in vertical nadir, and 4) images are mostly 2D. Recently, unoccupied aerial systems (UASs), due to their high imaging capabilities, have been used to study volcanic eruption sites (Müller et al., 2017), dykes (Dering et al., 2019), volcano-tectonic relations (Walter et al., 2018; Bonali et al., 2019) and active faults in volcanic areas (Rust and Whitworth, 2019), as well as faults and landslides in non-volcanic environment (Rathje and Franke, 2016; Gao et al., 2017). UASs are also known as drones, aerial photography systems and unmanned aerial vehicles. Recently, some studies have used the Structure from Motion (SfM) technique to create 3D Digital Outcrop Models (DOMs) of UAS-mapped areas (Benassi et al., 2017; Burns and Delparte, 2017; Cook, 2017; Pavlis and Mason, 2017), but none of these approaches has fully exploited the 3D nature of the modelled structures to allow the user to interact with the full 3D geometry of the model for measurement and mapping purposes. An attempt in this sense has been done by Gonzaga et al. (2017), although their approach is just focused on single, limited outcrops.

Here we present an approach that allows a more complete understanding of volcanic features for teaching, learning and research, using immersive VR based on real world 3D DOMs scenario. Our approach, in fact, establishes a framework that provides a unique blend of tools allowing: i) the study of geological or volcanological sites at a wide range of scales, from small outcrops to large areas, ii) wide range of measurements, and iii) wide range of exploration scenarios. Using three examples of volcanic areas with different features, we demonstrate the potential of this type of approach to optimize the users' geological experience by allowing them to move around outcrops and take quantitative measurements. Furthermore, this allows far more embracing contact and exchange with a wider audience; we started to present our immersive VR at schools, national and international exhibitions (e.g. Fig. 1a) open days, and with the public in all sorts of situations, provoking very positive feedbacks and popularizing volcanological sciences and geological features of volcanic areas. We also used the feedback from students and colleagues to improve our software and tools.

3D modelling and data input (Part I)

Our approach consists of creating immersive VR that provides scientists and students with virtual ways to study rock outcrops and collect measurements (e.g. Fig. 1b), replicating classical field activity. The first step consists of creating a high-resolution 3D DOM, which is based off a real world scene, with UAS surveys planned at a scale suitable for the research purposes and using the SfM workflow (e.g. James and Robson, 2014; James et al., 2017; Bonali et al., 2019). We would like to remark that 3D DOM can be also referred as "Virtual Outcrops (VO)" (Xu et al., 1999; Tavani et al., 2014) that, with our approach, can be studied in first person. A Wavefront Object File (OBJ) - in the form of a Tiled model - was selected to store the 3D geometry and texture, based on the UAS-collected high-resolution images, as it can be easily imported and managed in the Unity game engine (Unity is a cross-platform game engine developed by Unity Technologies, and a game engine is a software-development environment designed for people to build video games) (Krokos et al., 2019). The resolution and accuracy of the resulting model depends on the UAS camera resolution, UAS distance to target during photo acquisition, number of established ground control points and level of quality during SfM processing (details in Westboy et al., 2012; Bonali et al., 2019). For example, when flying about 25 m above the target, we achieve a resolution of 8 mm/pixel, as shown in our example of the Greek Metaxa mine that will be described below. All surveys in the present work have been done using a quadcopter equipped with a 20 MPX camera, including EXIF (Exchangeable Image file Format) information and GPS coordinates, provided by the integrated Satellite Positioning Systems GPS/GLONASS (referred to the WGS84 datum). Thanks to a built-in high precision 3-axis gimbal, flights are smooth, and the image collection is steady. The model we used provides constantly stable flights thanks to the integrated GPS system, including position holding, altitude lock and stable hovering. Hereunder we summarise the overall steps to produce a high-resolution 3D DOM (Part I of the overall workflow shown in Figure 1c).

The first step is to define the area to be surveyed, the UAS flight missions, including paths orientations and flight height, that can be planned and managed using dedicated software, particularly for pictures acquired in nadir orientation. The UAS has been manually driven to collect pictures with oblique orientation of the camera and to detail vertical cliffs. Photo overlap has also to be defined, as suggested by Gerloni et al. (2018), Bonali et al. (2019), Krokos et al. (2019) and Antoniou et al. (2019). In fact, it is recommended that UAS-captured photos should have an overlap of 90% along the path and 80% in lateral direction, in order to obtain a greater alignment of images and to reduce the distortions on the resulting texture. The photos have been captured every 2 seconds (equal time interval mode), with a constant velocity of 3 m/s (low speed) and in optimal light conditions suitable for the camera ISO range (100-1600) (Bonali et al., 2019).

In order to allow for the co-registration of datasets and the calibration of models resulting from SfM processing (e.g. Orthomosaics and DSMs), World Geodetic System (WGS84) coordinates of, at least, four artificial Ground Control Points (GCPs) must be established near each corner within each surveyed area and one in the central part (e.g. James and Robson, 2012; Turner et al., 2012; Westoby et al., 2012; James et al., 2017) for reducing the 'doming' effect resulting from SfM processing. Wherever possible, GCPs were surveyed with the Emlid Reach RS©, low-cost single frequency receivers (Rover and Base) in RTK configuration (with centimetre-level accuracy), finally correcting the z (altitude above the sea level) values of the GCPs using the regional geoid model to obtain the orthometric height for the models.

Focusing on data processing aimed at 3D DOM production, photos have been processed with the use of Agisoft Metashape (http://www.agisoft.com/). This is a SfM software becoming increasingly widely used in the geological community for both UAS and field based SfM studies for its user-friendly interface, intuitive workflow and high quality of points clouds (Benassi et al., 2017; Burns et al., 2017; Cook, 2017). The SfM technique allowed to identify matching features in different photos, collected along a defined flight path (Fig. 5b), and combined them to create a sparse and dense cloud, and the Wavefront OBJ Tiled model (further details in Stal et al., 2012; Westoby et al., 2012). The first step was to obtain an initial low-quality photo alignment, only considering measured camera locations (Reference preselection mode). After that, photos with quality value <0.5, or out of focus, were excluded from further photogrammetric processing, following the software user manual (Agisoft LLC, 2018). The focal length and photo dimensions were automatically detected by the software, after the import of digital images and then used for the subsequent calibration of the intrinsic parameters of the camera (principal point coordinates, distortion coefficients). After this first quality check, we added Ground Control Points (GCPs) in all photos, where available, in order to: i) scale and georeference the point cloud (and thus the resulting model); ii) optimize extrinsic parameters, such as estimated camera locations and orientations; iii) improve the accuracy of the final model. We then realigned the photos using high accuracy settings: as a result of this step, camera location and orientation were better established, and the sparse point cloud was computed by the software. The next step consisted in reconstructing the dense point cloud, calculated from the sparse point cloud, using a Mild depth filtering and medium/high quality settings. The 3D tiled model was then reconstructed using the dense cloud as source data for a Medium number of Face count and exported in the format OBJ tiled model. The information provided with the OBJ Tiled Model must be imported in the Unity game engine in order to replicate a real-world reference system.

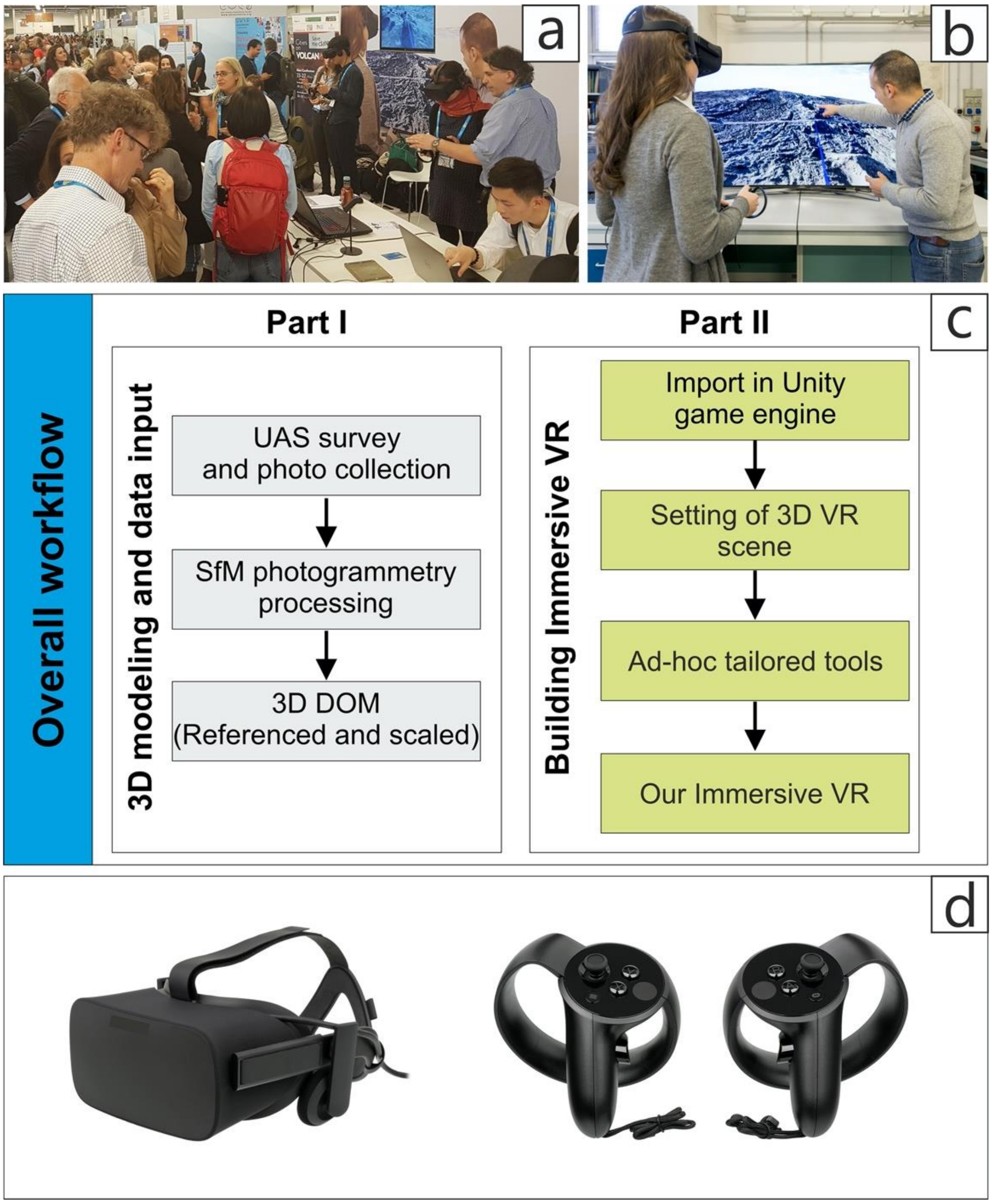

Figure 1. a) International outreach event using immersive VR in the framework of the the EGU General Assembly 2019; b) Example of teacher and student activity using immersive VR.; c) Processing workflow overview; d) VR headset on the left and sticks used to interact with the scene, on the right.

Building Immersive VR (Part II)

The target of our approach is to comprehensively simulate field experiences and observational behaviours of geoscientists using high-resolution datasets and models. Our approach provides interaction experiences realising navigation/exploration workflows that may not even be possible in the actual field, thus giving unique spatial awareness insights in comprehending complex volcanological processes. An example can be the monitoring of a steep slope on an active volcano, where uprising magma, intrusions, or earthquake shaking can destabilise the slope with the possibility of slope failure. These multiple hazards create a complex scenario that requires field inspection and collection of reliable field measures, but this can be impossible for the impending threats.

We developed a software that provides end users with a holistic view of an area of interest, by allowing exploration of specific features from several points of view and at a range of different scales (see supplemental videos 1, 2 and 3), starting from technologies commonly used in entertainment applications (such as video games). Those include modern game engines (Unity, https://unity.com) combined with Virtual Reality devices (Oculus Rift, https://www.oculus.com/). Unity supports modularity and extensibility to build modular assets that are easily expanded and sustained long term. Furthermore, Unity supports several file formats as used in industry-leading 3D applications (e.g. 3DS Max, Blender). Unity is also well documented as it is supported by large numbers of communities of software developers. Although the development of our software framework is based on the Unity game engine and Oculus, we have deployed generic functionalities of game engines and head mounted displays abstracting as much as possible from specific realisations.

Our system supports a high-performance visualisation layer underpinning a comprehensive set of navigation, interaction and accurate measurement tools to allow geoscientists full appreciation of on-shore settings. Unlike other software for handling digital outcrops (VRGS, www.vrgeoscience.com, or MOSIS of Gonzaga et al., 2017), our focus has been on developing a fully integrated software suite for seamless VR navigation of wide areas. Moreover, our software enables, via appropriate controls, rich user interactions and on-the-fly visualisation adjustments. The uniqueness of our framework lies on the modularity of its underlying architecture enabling support for multiple mechanisms to select and deploy navigation approaches. It enables incorporation of several import and export mechanisms to ensure the creation of data products with long-term sustainability. The 3D DOM/Tiled model approach is built upon UAS-based SfM techniques and is thus able to provide centimetric pixel size resolution for textures. The use of Wavefront OBJ Tiled model was successfully designed and tested by Krokos et al. (2019) who applied it to areas of different extents and resolutions, respectively ranging 50-1000 m (along the longest) and 0.8-4 cm, also considering the present work. The use of 3D DOM allows improved representations of geometrical features especially around regions that are vertical to the terrain.

Starting from the processed datasets (see Part I), the user must perform few preliminary operations in order to make the scene navigable: an invisible object called “collider” must be assigned to each mesh for the purposes of physical collisions, and the scene has to be properly referenced and scaled by employing information derived from SfM processing. Thus, the scene dimension (in meters) and the corresponding geographic coordinates must be defined, as well as the altitude referred to the 3D reconstructed model. All informations are included in the Tiled Model folder, in Wavefront OBJ format, provided by SfM software we used. Finally, to optimize the rendering performance of the scene, we also suggest the use of Unity Levels of Detail (LODs) methodology to reduce the number of details shown when the model is far away from the camera. For this case, in the Tiled Model folder different level of details for the model that can be set up in Unity engine are already provided.

First of all, the user will see the scenario in first person and walk on a “solid ground surface” to allow them to move around within the virtual scene, or the user can fly over the area, allowing him to have a different view of the outcrop that may open perspectives that are not possible to experience during real fieldwork (see supplemental video 1).

Our software also includes a series of tools embedded in the VR environment, represented by symbols that appear on the screen by pressing a button of the joystick (Fig. 1d) (see supplemental video 2). Such tools have been developed by our research team that comprises also software developers and required some months of work in strict collaboration with geologists. The tools were in fact customized on the classical needs of geologists and volcanologists in the field, which are of paramount importance to quantitatively describe the features of a given area. Directly on the screen you can choose the tool you need. The tools have been developed with the idea of allowing the user to take measurements like being in the field, but with the advantage that the user can change the angle of view in order to better select the proper perspective to take measures. Once you have selected the tool, you point with the joystick the object to be analysed. A tool allows to assess geographic location by coordinates. Another tool allows to select a point feature. By other tools it is possible to map polygons and lines, and measure areas. In these cases, it is necessary to click with the joystick in different points on the virtual ground. Other tools allow the measurement of dip, inclination, and azimuth of an object. By clicking on two points with another tool, it is possible to measure thickness of volcanological objects such as bedding, dykes, etc, and with another tool it is possible to reconstruct the topographic profile. Finally, the system allows to take virtual photographs and notes.

Case studies

The Dallol Volcano, Ethiopia

The active Dallol Volcano was one of the most inaccessible places on Earth, but recently has opened up due to a new road, and there is rapid increase of tourists visiting the incredible geothermal manifestations. This has led to increased risk from multiple geohazards and from the extreme climate. Assessing hazards requires detailed topographic and geologic information, but the area is dangerous and hard to access. Thus, the area was surveyed by UAS and data was processed following our approach (Fig. 2a). Particularly, the 3D DOM is based on 229 pictures acquired with nadir camera orientation, at a flight height of 113 m, obtaining a texture resolution of 2.87 cm/pixel over an area of 0.176 km^2. Photo alignment has been processed with high quality setting and using Generic and Reference preselection. The dense cloud has also been built up using high quality, whereas GCPs have been not collected in the field due to hard logistic condition. In the VR environment, we have been able to access areas impossible in the field, making measurements and observing features. We have detected different types of dykes and found erupted products (Fig. 2b). We have also characterized and quantified salt karst structures, to start integrating measurements into a hydrogeological–volcanological model. Tower morphologies are topped by a 3-m thick white eruption deposit. A tower of salt layers has a vertical sided doline (sink hole) which is 6 m across, and at least 5 m deep, set on a flat area above a 17-m high cliff. Dykes of red clay, possibly filled karst pathways, from Dallol’s central hydrothermal area, are mapped and selected measurements shown. A white dyke, made of salt and magma is up to 17 m wide outcropping over 1000 m^2. A small dry river channel between source and sink holes is 53 m long.

This Dallol reconstruction has already been shown in Ethiopia and internationally, and has been used to get opinions of stakeholders on the nature of the geological object, its use in geotourism and possibilities of protection. Users who know the area, mostly geologists so far, have expressed amazement at the ability to see the geological features that they have missed in the field. Prospective visitors (non geologists) have also expressed amazement and wonder at being able to fly around such a landscape.

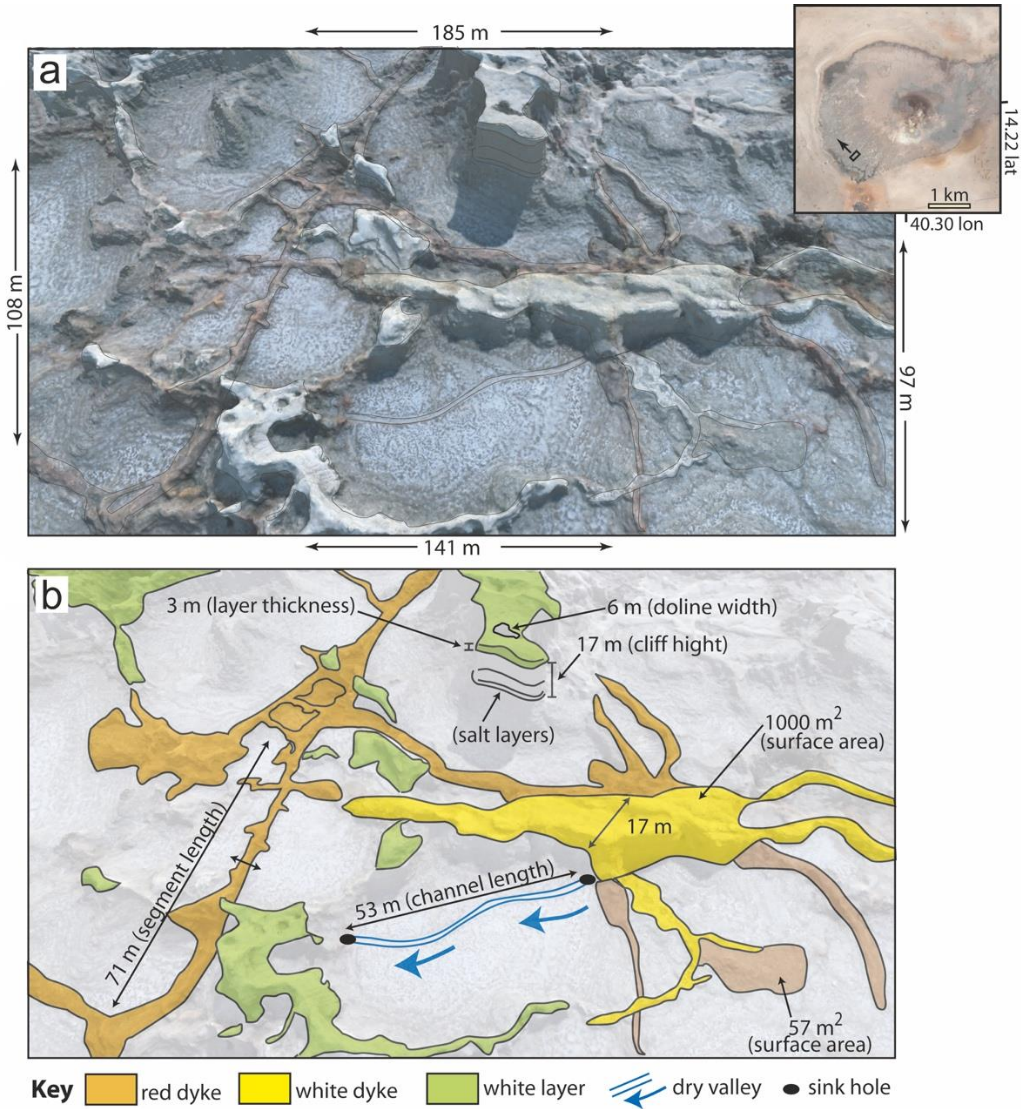

Figure 2. a) 3D representation of an area of the Dallol volcano (Ethiopia) captured using camera tool in Immersive VR. (distances show the measured length of the edges of the perspective). Inset shows full view of Dallol volcano and locates the area described, with arrow for view direction. b) Interpretation with some examples of quantitative measurements taken in Immersive VR environment. Selected features mapped in this area include red dykes related to infilling of the karst system, a white dyke magmatic–hydrothermal intrusion, white eruptive layers, and sink holes.

The Metaxa mine, Greece

The Metaxa Mine is a unique geotope of Santorini volcano (Greece) where the pumice layers of the famous Late Bronze Age (LBA) (well-known also as Minoan) eruption are exposed (see supplemental video 3). It is nowadays abandoned and it is located in the central part of Santorini island, overlooking the famous Santorini caldera (Figs. 3a, b). The latter was created after the catastrophic Minoan eruption (Friedrich et al., 2006; Druitt, 2014), which has influenced the decline of the Minoan civilization on Crete, making it an iconic event in both volcanology and archaeology disciplines. The mine contains the so-called "Famous section" which shows the pumice layers of the eruption along a length of 150 m (see the pictures collected from our immersive VR in Fig. 3c) and classical field activity (Fig. 3d). From the area which is located on the east side of the Famous section, about 1.3 million m^3 were excavated in the early years of mining. A total of 4.5 million m^3 is estimated to have been extracted from the Metaxa mine, according to 3D digital model of the terrain (Antoniou et al., 2019). Our approach provides an excellent way to access the vertical and overhanging cliffs in immersive VR and to analyse it in detail in a way that was not possible before. The resulting 3D DOM has a pixel resolution of 8 mm and allows the recognition and measurement of the thickness not only of the main different pyroclastic layers, but also of the single eruptive pulse events (Fig. 3d), and even the diameter (down to 1-2 cm) of the lithic clasts embedded in the vertical exposure (Fig. 3e). Pictures have been taken in two main different missions: the first was devoted to capture a set of photos in nadir camera view (n=1121) to cover the whole selected area; in the second we collected photos (n=992) of the vertical outcrops with the camera oriented orthogonal to the vertical cliff, in order to add as much details as possible to the resulting model. Photo alignment has been processed with high quality setting and both using Generic and Reference preselection, the dense cloud has also been built up using medium quality, considering the extent and resolution of the final model, and a set of 20 uniformly distributed Ground Control Points have been included in order to co-register the 3D model to the World Geodetic System (WGS84) (Smith et al., 2016; Esposito et al., 2017). The resulting 3D DOM is as large as 349 x 383 m.

In Figure 3c, we can distinguish: a) The 103-cm-thick Pre-Minoan base, b) a reverse-graded pumice fall deposit of 258 cm thickness from the first main Plinian eruption (Phase 1, P1), c) the 731-cm-thick pyroclastic surge deposits with multiple bedsets, dune-like bedforms with wavelengths of several meters or more and bomb sag horizons (Phase 2, P2) (Bond and Sparks 1976; Heiken and McCoy, 1984; McClelland and Thomas,1990), and d) within eruptive Phase 2, it is easy to distinguish the lowest fine-grained bedset (P2a) from the overlying coarse grained sequence of multiple bedsets (P2b) and the 498-cm-thick fine-grained, nonwelded ignimbrite (P4). The precursory explosion phase (P0) is characterized by a thin lapilli fallout layer of 10 cm in thickness, shown in the field-panoramic view of the Famous section (Fig. 3f). These measures have been obtained by our VR approach and similar detailed values did not exist for the site. At general, Phase 1 corresponds to a Plinian eruption, whereas Phase 2 was characterized by syn-plinian pyroclastic surges. In Phase 3, eruption of 'cold' phreatomagmatic pyroclastic flows constructed a large tuff cone that filled the old caldera, cutting it off from the sea. In Phase 4, eruption of hot pyroclastic flows took place from multiple subaerial vents, associated with caldera collapse that enlarged and deepened the ancient caldera (Nomikou et al., 2016).

For science popularization and communication, the VR reconstruction of Metaxa mine is being used in a UNESCO Geosciences Programme project (IGCP project 692 "Geoheritage for Geohazard Resilience") to raise awareness in the geological community and in the more general public about the value of this site, which is in urgent need of protection and development as a unique heritage demonstration of the powerful volcanic eruptions of Santorini. Moreover, this site has great value in regards to the relations between volcanic activity and humans: this mine is part of Santorini history, especially in relation to the economic development of local populations, who in difficult times were able to find income opportunities thanks to the extraction of pumice materials. The Metaxa mine is not only a site of international scientific relevance, but also an industrial heritage site that, as every monument, deserves special attention. The VR model has also been presented at Santorini administrations in order to explain in a more effective way the features present in the field. Finally, in regards to teaching, our VR model has been used to train Msc and PhD students of different European countries during a series of International Summer Schools organized in the framework of the 2018-2020 project Erasmus+ KA2 "3DTeLC: Bringing the 3D-world into the classroom: a new approach to Teaching, Learning and Communicating the science of geohazards in terrestrial and marine environments".

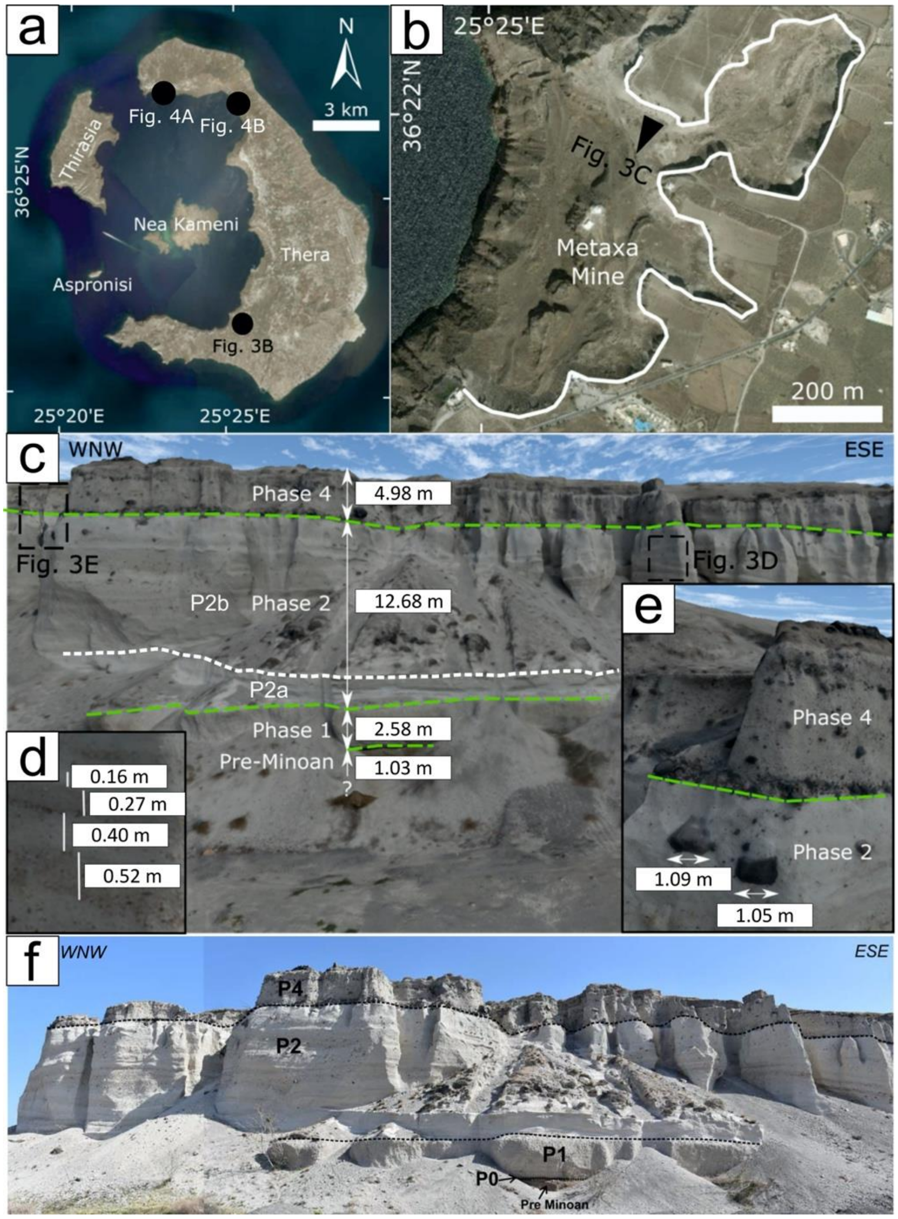

Figure 3. Metaxa mine example: a) Location in Santorini island. b) Location of the reconstructed outcrop used in this example. c) 3D view of the "Famous section" showing the main strata of the various Minoan eruptive phases and measured thickness in immersive VR. d) and e) Examples of measurement of lithic clasts at vertical outcrops by VR. f) Field-panoramic view of the "Famous section" (modified after Antoniou et al., 2019).

Outstanding dykes along the Santorini's caldera wall, Greece

Santorini is a unique place where it is possible to study outstanding feeder and non-feeder dykes (e.g. Figs. 4a-b), cropping out along the northern part of the caldera wall. Their study is of paramount importance for better understanding processes related to the propagation paths of fractures/dykes through layers with dissimilar mechanical properties, since they are emplaced in a highly heterogeneous and anisotropic host rock. Their mapping could provide valuable insights on the topic. In fact, Browning et al. (2015) started this work collecting detailed measurements of dykes at the sea level in some accessible sites. The problem is that most dykes crop out along inaccessible vertical cliffs (up to 300 m high) or dangerous areas with hard logistic conditions (continuous rockfalls), and thus their characterisation can only be done very locally, at the sea level, and cannot be measured along their whole outcropping range. We give here an example to illustrate how it is possible to overcome such difficulties. We also emphasize that this is just an example, but a full study of the whole cliff is underway by VR and will be published in another paper. This represents measurements at a site that was previously inaccessible. We reconstructed a text-book case of a dyke (Figs. 4c-e) using UAS-collected pictures and SfM processing, obtaining a model with a texture resolution of 4 cm/pixel. Pictures have been collected with oblique orientation of the camera using a quadcopter equipped with a 20 MPX camera. It has been manually driven, at a constant velocity of 3 m/s and capturing pictures every 2 seconds (equal time interval mode), flying between the sea level and a maximum height of 130 m. Regarding the processing, photo alignment has been processed with high quality setting and both using Generic and Reference preselection. The dense cloud has been built up using medium quality, and a set of 5 GCPs have been included in order to co-register the 3D model to the World Geodetic System (WGS84) (Smith et al., 2016; Esposito et al., 2017). The resulting 3D DOM is as large as about 1000 x 340 m.

Different from the two examples described before, in this case quantitative data have been collected flying in front and around the dyke, instead of walking within the 3D DOM. Using the measurement tools, we collected dyke inclination and thickness from the sea level up to an altitude of 100 m, providing unique and new data (Figs. d-e). The selected dyke is characterised by a dip angle of about 80° at the sea level, with a NW dip, becoming vertical between 30-50 m a.s.l. Between 50-90 m a.s.l., its inclination decreases to 70-80°. The thickness is between 1.0-1.5 m from sea level to an altitude of 20 m, and increases up to 2-2.5 m at 80-90 m a.s.l. These results demonstrate that the immersive VR we developed has a great potential to fully study the dyke swarm emplaced in the Santorini volcano, as well as any other magma plumbing system exposed at vertical cliffs. Even though field studies are vital for mapping and understanding the geological processes on Earth, in several cases, like the one here shown, classical surveys are impossible, whereas our approach represents a solution.

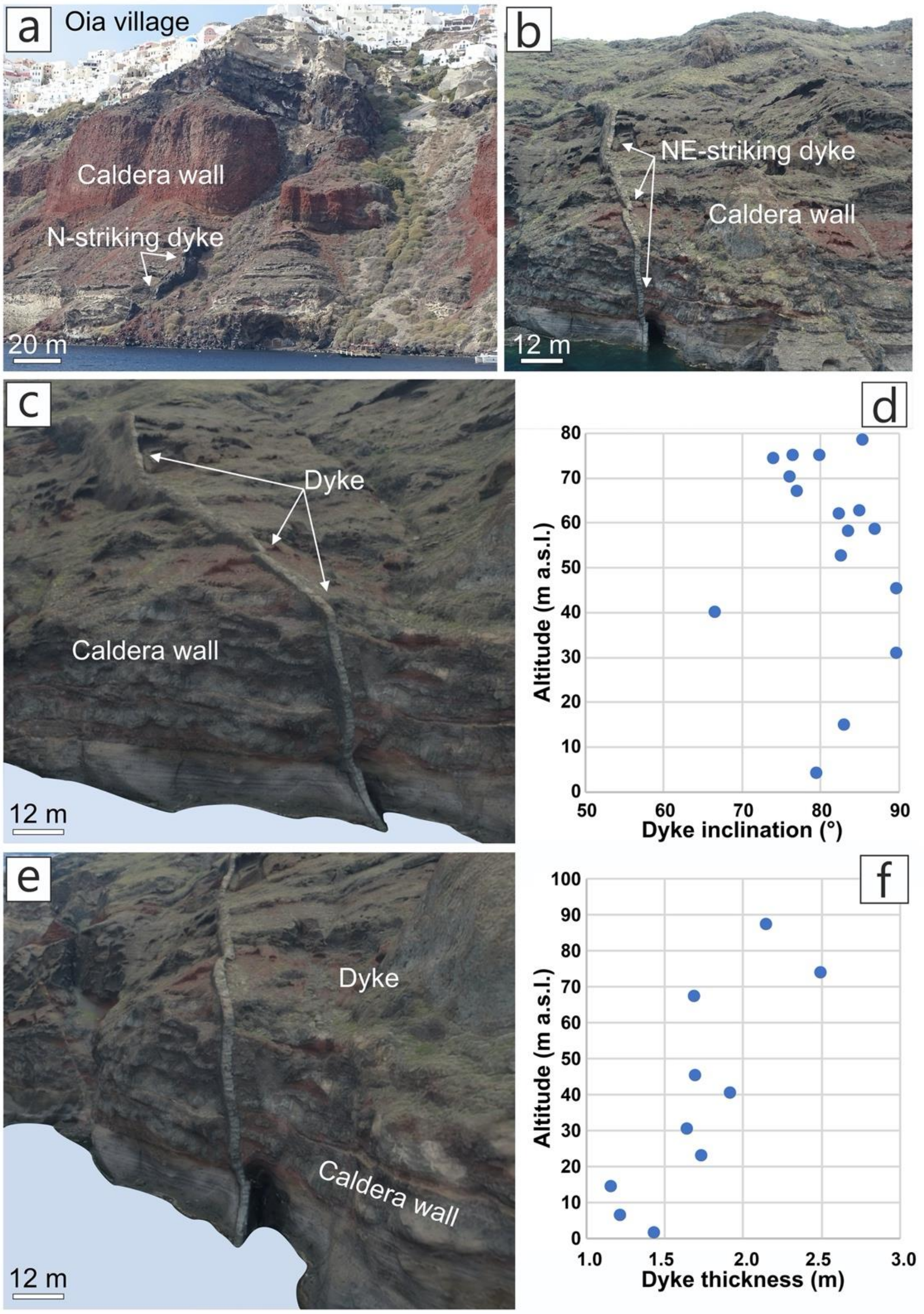

Figure 4. a) Boat-collected picture of a vertical dyke outcropping along the NW part of the caldera wall, in correspondence of the Oia village; houses for scale, the location is provided in Figure 3a. b) UAS-collected picture of a mostly vertical NE-striking dyke, outcropping in the NE part of the caldera wall, location is marked in Figure 4a (picture courtesy of Luca Fallati). c) and e) show the same dyke of Figure 4b but the pictures have been collected in immersive VR, as well as all measurements regarding dyke inclination and thickness presented in figures d) and f).

Discussion

Volcanic areas are of high interest for scientific and economic reasons, such as minerals, soil fertility and tourism. In the case of active volcanoes, they can pose significant threats to large populations and infrastructures, and the latter can be temporarily or permanently interrupted with significant repercussions for economic and social stability. Volcanic areas can also have spectacular features that attract the attention of the wider public, who is keen to experience and know more about them, but that is also a risk if people go close to hazardous sites. Therefore, the reconnaissance, mapping, quantification and understanding of volcanic areas is increasingly important, together with the communication of volcanic hazards.

To date, the study of volcanic areas has relied largely upon standard field data collection techniques, but these can be affected by logistic and time constraints or difficulties in accessing dangerous sites. For example, an impending eruption requires immediate data collection or observations of the crater zone, which can be inaccessible or extremely dangerous to approach. Similarly, very rugged terrains and steep slopes represent hard logistic conditions. The approach described here links together geoscience, remote sensing and game engine technologies with an innovative, integrated software solution to create opportunities to collect data in remote areas or dangerous zones, using a fully immersive VR environment.

The three case sites presented, show how important and useful our approach can be. We have focused here on onshore examples, but we stress that our approach can also be applied to offshore environments. The Dallol Volcano shows a case where several complex characteristics can be detected and measured in an extremely inhospitable environment. The magma and karst paths of the volcano are now 3D objects that stand out from a highly dissected landscape. The approach here allows careful measurement of dyke thickness, length, strike, and dip angle, allowing a complete reconstruction of the karst and volcanic plumbing system. It is also possible to immediately calculate the area of exposures from these various outcrops, and to inspect inaccessible cliffs and deep hollows, allowing other 3D objects, such as sink holes to be explored and measured. The Dallol example also shows how visually attractive such an experience can be for engaging with the greater public. This is particularly true in the case of spectacular natural features that otherwise would be impossible to visit.

The Metaxa mine provides exposure of the Minoan eruption and illustrates how detailed measurements can be obtained along inaccessible vertical cliff sections. It has been possible to measure bed thickness and dimensions of single cm-size lithic clasts hosted in the volcanic strata. Furthermore, this example shows that our approach can be used to demonstrate the value of the site and the need for its protection and future development. VR acts as a motor for a wider appreciation of this site, and can be used in political and administrative meetings to effectively communicate with decision makers.

The Santorini dyke we presented (Fig. 4) is part of a large dyke swarm affecting the northern part of the caldera where it is mostly impossible to collect quantitative measures to characterize dyke geometry and thickness, except for near the sea level. This is due to the continuous rock falling and the absence of safe paths to reach the dykes along the 300-m-high caldera wall. Using the immersive VR, we provided, for the first time, measurements characterizing dyke thickness and geometry with continuity from the sea level upwards. We demonstrated that this approach is fundamental to fully study the dyke swarm and to provide new outcomes related to diking process in highly heterogeneous and anisotropic host rock, a topic of paramount importance for volcanic hazard assessment (Gudmundsson, 2006).

The three cases of 3D rendering in immersive VR are also examples of how this approach can be used for outreach purposes; for example, a Santorini committee is currently using the model as part of its proposal to classify the mine as a unique example of the Minoan eruption, serving as an open-air museum. This 3D model records important scientific and cultural heritage and will virtually preserve the integrity of the site. This permanent record of the site will allow future scientists to interact with the original outcrops, and inform a non-academic audience about the historical and volcanological aspects of this site that provides a unique window of the Minoan eruption (Antoniou et al., 2019). Equally, the Dallol example is being used to communicate the unknown and un-valued nature of the site to both locals, authorities and tourists, in order to protect this natural heritage (Vereb et al., 2019). Santorini dyke swarm is a unique example to popularize the concept of magmatic intrusions, feeder and non-feeder dyke and volcanic eruptions. This showcases how a volcano interior is.

In general, our approach enables anyone to create models based on real world images with unprecedented detail, georeferenced, and fully explorable. This allows the operator to take measurements in an immersive VR 3D environment. Moreover, since outcrops can also change over time, our approach allows to make a quick and direct comparison of the area development. For example, it is possible to quantitatively compare pre- and post-eruption craters. This approach allows collection of quantitative data similar to standard field data collection. This represents a scenario where the experience of the geologist/volcanologist, which is critical in carrying out the interpretation, can be fully exploited, and fully communicated to all end users. Of course, VR cannot substitute field survey where this is feasible (but it can contribute to collect more geometric data), and cannot replace field trips for students where they can also take samples and see finer rock textures and minerals.

Conclusions

Collecting in-situ data from field localities is essential in geological and volcanological sciences for teaching and research. We proposed an approach that ensures that studies can be as effective as possible even where areas are difficult or impossible to access (e.g. active volcanic areas or vertical slopes). We combine existing technologies of remote sensing, UAS, SfM, game engines and gaming headsets (e.g. Oculus Rift) with new software that allows real-time navigation in real world-based immersive VR and quantitative measurements using specially designed tools for typical geological mapping. This method has been showcased using three sites with different volcanological and volcanotectonic features to illustrate how relevant quantitative field data can be collected in inaccessible areas using VR. The results indicate significant potential for recording sites for virtual research and also for educational purposes and exploration by future generations. There is a high potential for improving communication between scientists and the public about the shared experience of natural objects; “bringing” the field in a room through immersive VR means that non-scientists can have a real perception of natural phenomena. This is scientific awareness and understanding of the ongoing volcanological processes in a way that previously was not possible, an essential step for making informed choices and behaviours.

Acknowledgements

We greatly appreciated the useful comments on an early version of the manuscript of the Editor, Jacopo Taddeucci, and two anonymous reviewers. The UAS survey of the Dallol volcano was made in collaboration with Olivier Grunewald (https://www.oliviergrunewald.com/). Funded by project ACPR15T4_00098

“Agreement between the University of Milan Bicocca and the Cometa Consortium for the experimentation of cutting-edge interactive technologies for the improvement of science teaching and dissemination” of Italian Ministry of Education, University and Research (coordinated by A. Tibaldi), and project Erasmus+ Key Action 2 2017-1-UK01-KA203-036719 "3DTeLC - Bringing the 3D-world into the classroom: a new approach to Teaching, Learning and Communicating the science of geohazards in terrestrial and marine environments" (coordinated by M. Whitworth). The examples are integrated into the UNESCO International Geosciences Program project 692 “Geoheritage for Geohazard Resilience” (coordinated by B. van Wyk de Vries). This article is also an outcome of Project MIUR – Dipartimenti di Eccellenza 2018–2022 and ILP Task Force II. Agisoft Metashape is acknowledge for photogrammetric data processing.

References

Andrade, A., 2015. Game Engines: A Survey, EAI Endorsed Transactions on Serious Games, 2 (6),150615, DOI: 10.4108/eai.5-11-2015.150615.

Antoniou, V., Nomikou, P., Bardouli, P., Sorotou, P., Bonali, F., Ragia, L. and Metaxas, A., 2019. The story map for Metaxa Mine (Santorini, Greece): A unique site where history and volcanology meet each other. In: Proceedings of the 5th International Conference on Geographical Information Systems Theory, Applications and Management, 1, 212-219. DOI: 10.5220/0007715602120219

Benassi, F., Dall'Asta, E., Diotri, F., Forlani, G., Cella, U.M. di, Roncella, R., Santise, M., 2017. Testing accuracy and repeatability of UAV blocks oriented with gnss-supported aerial triangulation. Rem. Sens., 9 (2), 172.

Bonali, F.L., Tibaldi, A., Marchese, F., Fallati, L., Russo, E., Corselli, C., Savini, A., 2019. UAV-based surveying in volcano-tectonics: An example from the Iceland rift. Journal of Structural Geology, 121, 46-64.

Bond, A. & Sparks, R.S.J. (1976). The Minoan eruption of Santorini, Greece, Journal of the Geological Society, London, 132, 1–16.

Burns, J.H.R., Delparte, D., 2017. Comparison of commercial structure-from-motion photogrammety software used for underwater three-dimensional modeling of coral reef environments. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42. 127–131.

Browning, J., Drymoni, K., Gudmundsson, A., 2015. Forecasting magma-chamber rupture at Santorini volcano, Greece. Scientific reports, 5, 15785.

Christopoulou, E., and Xinogalos, S., 2017. Overview and Comparative Analysis of Game Engines for Desktop and Mobile Devices. International Journal of Serious Games, 4(4), DOI: https://doi.org/10.17083/ijsg.v4i4.194.

Cook, K.L., 2017. An evaluation of the effectiveness of low-cost UAVs and structure from motion for geomorphic change detection. Geomorphology 278, 195–208.

Dering, G.M., Micklethwaite, S., Thiele, S.T., Vollgger, S.A., Cruden, A.R., 2019. Review of drones, photogrammetry and emerging sensor technology for the study of dykes: Best practises and future potential. Journal of Volcanology and Geothermal Research, 373, 148-166.

Druitt, T.H., 2014. New insights into the initiation and venting of the Bronze-Age eruption of Santorini (Greece), from component analysis. B. Volcanol, 76 (2), 794.

Druitt, T. H., Edwards, L., Mellors, R., 1999. Santorini volcano. Geol. Soc. Lond. Mem. 19, 1–165.

Esposito, G., Mastrorocco, G., Salvini, R., Oliveti, M. and Starita, P. (2017). Application of UAV photogrammetry for the multi-temporal estimation of surface extent and volumetric excavation in the Sa Pigada Bianca open-pit mine, Sardinia, Italy. Environmental Earth Sciences, 76(3), p.103.

Friedrich, W. L., Kromer, B., Friedrich, M., Heinemeier, J., Pfeiffer, T. and Talamo, S., 2006. Santorini eruption radiocarbon dated to 1627-1600 BC. Science, 312(5773), 548-548.

Gao, M., Xu, X., Klinger, Y., van der Woerd, J., Tapponnier, P., 2017. High-resolution mapping based on an Unmanned Aerial Vehicle (UAV) to capture paleoseismic offsets along the Altyn-Tagh fault, China. Sci. Rep., 7 (1), 8281.

Gerloni I.G., V. Carchiolo, F.R. Vitello, E. Sciacca, U. Becciani, A. Costa, S. Riggi, F.L. Bonali, E. Russo, L. Fallati, F. Marchese, A. Tibaldi, 2018. Immersive Virtual Reality for Earth Sciences. Proceedings of the Federated Conference on Computer Science and Information Systems, 15, 527–534, DOI: 10.15439/2018F139.

Gonzaga, L., Veronez, M.R., Alves, D.N., Bordin, F., Kannenberg, G.L., Marson, F.P., Tognoli F.M.W., Inocencio, L.C., 2017. MOSIS - Multi-outcrop sharing & interpretation system. In 2017 IEEE International

Geoscience and Remote Sensing Symposium (IGARSS), 5209-5212), DOI: 10.1109/IGARSS.2017.8128175.

Granshaw, F. D., & Duggan-Haas, D. (2012). Virtual fieldwork in geoscience teacher education: Issues, techniques, and models. Geological Society of America Special Papers, 492, 285-303.

Gudmundsson, A. (2006). How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes. Earth-Science Reviews, 79(1-2), 1-31.

Heiken, G., McCoy, F., 1990. Precursory activity to the Minoan eruption, Thera, Greece. In: Hardy D.A. (ed.) Thera and the Aegean World III, vol 2. Thera Foundation, London, 13–18.

James, M.R., Robson, S., 2014. Mitigating systematic error in topographic models derived from UAV and ground-based image networks. Earth Surf. Process. Landforms 39 (10), 1413–1420.

James, M.R., Robson, S., d'Oleire-Oltmanns, S., Niethammer, U., 2017. Optimising UAV topographic surveys processed with structure-from-motion: ground control quality, quantity and bundle adjustment. Geomorphology, 280, 51–66.

Krokos, M., Bonali, F.L., Vitello, F., Antoniou, V., Becciani, U., Russo, E., Marchese, F., Fallati, L., Nomikou, P., Kearl, M., Sciacca, E., Whitworth, M., 2019. Workflows for virtual reality visualisation and navigation scenarios in earth sciences. 5th International Conference on Geographical Information Systems Theory, Applications and Management: GISTAM 2019, SciTePress.

Lawson, E., 2015. Game Engine Analysis (www. gamesparks. com/blog/gameengine-analysis/).

McClelland, E., Thomas, R., 1990. A palaeomagnetic study of Minoan age tephra from Thera. In: Hardy, D.A. (ed.) Thera and the Aegean World III, Vol. 2 Earth Sciences, Thera Foundation, London, 129–138.

Müller D., Walter T.R., Schöpa A., Witt T., Steinke B., Gudmundsson M.T., Dürig T., 2017. High-resolution digital elevation modeling from TLS and UAV campaign reveals structural complexity at the 2014/2015 Holuhraun eruption site, Iceland. Front. Earth Sci., 5:59, doi: 10.3389/feart.2017.00059.

Nomikou, P., Druitt, T. H., Hübscher, C., Mather, T.A, Paulatto, M., Kalnins, L.M., Kelfoun, K., Papanikolaou, D., Bejelou, K., Lampridou, D., Pyle, D.M., Carey, S., Watts A.B , Weiß, B. & Parks, M.M., 2016. Post-eruptive flooding of Santorini caldera and implications for tsunami generation, Nature Communication.

Pavlis, T.L., Mason, K.A., 2017. The new world of 3D geologic mapping. GSA Today, 27 (9), 4-10.

Rathje, E.M., Franke, K., 2016. Remote sensing for geotechnical earthquake reconnaissance. Soil Dynamics and Earthquake Engineering, 91, 304-316.

Rust, D. and Whitworth, M., 2019. A unique 12 ka subaerial record of rift-transform triple-junction tectonics, N.E. Iceland. Scientific Reports, 9:9669. https://doi.org/10.1038/s41598-019-45903-8

Smith, M., Carrivick, J. and Quincey, D. (2016). Structure from motion photogrammetry in physical geography. Progress in Physical Geography: Earth and Environment, 40(2), pp.247-275.

Tavani, S., Granado, P., Corradetti, A., Girundo, M., Iannace, A., Arbués, P., Muñozb J.A., Mazzoli, S., 2014. Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran). Computers & Geosciences, 63, 44-53.

Trexler, C. C., Morelan, A. E., Oskin, M. E., & Kreylos, O. (2018). Surface slip from the 2014 South Napa earthquake measured with Structure from Motion and 3-D Virtual Reality. Geophysical Research Letters, 45(12), 5985-5991.

Vereb V., van Wyk de Vries, B., Hagos, M., 2019. Remote sensing monitoring and geosite assessment of Dallol, Ethiopia. Putting an isolated and deserted area on map with geoheritage and resilience Geophysical Research Abstracts, 21, EGU2019-5640.

VGRS, 2017, (http://www.vrgeoscience.com).

Walter, T.R., Jousset, P., Allahbakhshi, M., Witt, T., Gudmundsson, M.T., Hersir, G.P., 2018. Underwater and drone based photogrammetry reveals structural control at Geysir geothermal field in Iceland. J. Volcanol. Geother. Res., doi.org/10.1016/j.jvolgeores.2018.01.010.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179, 300-314.

Xu, X., Aiken, C. L., & Nielsen, K. C., 1999. Real time and the virtual outcrop improve geological field mapping. Eos, Transactions American Geophysical Union, 80(29), 317-324.

Zhao, J., Wallgrün, J. O., LaFemina, P. C., Normandeau, J., & Klippel, A. (2019). Harnessing the power of immersive virtual reality-visualization and analysis of 3D Earth science data sets. Geo-spatial Information Science, 1-14.